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Numerical Weather Prediction

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Abstract

This article is being published in the book "Geophysical Predictions" (National Academy of Sciences, Washington, D. C., 1978). The book covers predictions of a wide variety of phenomena in the atmosphere, hydrosphere, and solid earth. Just as the book is, this article is addressed to the layman with a science education. It is thus not addressed specifically to the meteorologist, but it contains certain information about the weather services, and the impact of numerical weather prediction on them, that I believe will interest those in the meteorological community who have not had close associations with the service side of our house.

The weather services are principally concerned with weather and river forecasting, and serve virtually all of the general public and the entire economy of our nation. Numerical weather prediction is at the core of the complex set of forecast services, and more accurate forecasts depend on progress in numerical weather prediction more than on anything else. This is as true now as it has been during the 20-odd years since operational numerical weather prediction began. Progress has been, and still is, paced by advances in computer power. Numerical weather prediction has seen a succession of four generations of computer hardware, and during its 20-year era has halved the overall errors in wind forecasts at all levels up to 12,000 m, and has improved the accuracy of forecasts of whether or not precipitation will fall. One of the most important forecasts, however, that of how much precipitation will fall, has been little improved for fifteen years, although there was a dramatic improvement around the turn of the 1960's. Recent research results, however, indicate that the greatest improvements will be made in this area during the coming decade.

The setting: weather services

More people are more concerned more continually with weather than with any other class of geophysical phenomena. Ask the man in the street, and some may grumble, but all will agree that accurate weather forecasts are important to them. The National Weather Service provides a multitude of services to the nation, and most are based on round-the-clock guidance prepared and disseminated from a central location near Washington, D. C. The guidance helps forecasters in the field do their job, and is prepared with methods that have come to be called numerical weather prediction. The development of numerical weather prediction has revolutionized the practice of weather forecasting, and has led to gradual improvements in weather services over the past twenty years. For the reader to fully appreciate the importance of this development, a brief description of the national forecast service will be given; what it is, how it is organized, and how numerical weather prediction fits into it.

Many of the weather services are unknown to the general public, but everyone is familiar with the public forecasts. The purpose of the public forecasts is to protect lives and property and to plan work, recreation, commerce, and travel. Besides the routine daily forecasts, advance warnings are issued of dangers such as tornadoes, hurricanes, flash floods, heavy rains, blizzards, heavy snow, cold waves, ice storms, hazardous driving conditions, high winds, and sand storms. Because weather forecasts are highly perishable, rapid communications are required for collecting observational data and for disseminiating forecasts. The 300 or so offices of the National Weather Service are linked together with teletype and facsimile networks, and during the next few years a conversion to more modern equipment will take place, involving mini-computers and cathode-ray-tube display devices.

An essential link in the chain of communications is between the local office and the general public. Prominent in this link are the news media: television, radio, and newspapers. A federally funded teletypewriter system, NOAA Weather Wire Service, services about 2500 radio and TV stations and newspapers. In more than 200 areas cable TV companies continuously display local weather information received by NOAA Weather Wire Service. The federal government pays the line charges, while the subscribing media support terminal equipment costs. The National Weather Service and telephone companies in 62 cities have installed automated telephone answering services to handle incoming calls for local weather forecasts. More than a half-billion calls annually are handled in this manner.

The National Weather Service continuously broadcasts weather information on the VHF-FM band from 134 stations. The NOAA Weather Radio system is rapidly expanding; by the end of 1979 a total of 330 such stations are planned that will cover 90% of the national population. Three frequencies are used, 162.4, 162.475, and 162.55 MHz, and special radio receivers must be used. They need not be expensive, however, and are easily obtained; for example, many department stores carry them. Some receivers are equipped with an alarm device that is activated by the broadcast to warn of hazardous weather.

There are presently 18 meteorologists in the field dedicated to the job of preparing communities and individuals to respond to forecasts and warnings. Plans are to expand this staff to 39 by 1980. These meteorologists work with local people, conducting preparedness meetings, recruiting and training tornado spotters, providing guidance to establish emergency warning centers, promoting building and safety codes, aiding in establishing evacuation routes in hurricane-prone coastal areas, assisting communities in developing flash flood warning systens, and enlisting news media for fast dissemination of warnings. They work closely with news media, public safety officials, and school officials in efforts to increase public understanding and response to warnings.

Among specialized services are those for aviation, both commercial and private. Weather observations are taken at more than 900 airports. Several million briefings are given to pilots each year. Virtually every commercial flight within or departing U.S. territory flies on a flight plan made from wind and temperature forecasts provided by computer-to-computer links with the National Meteorological Center. This information covers the globe everywhere commercial craft fly. There are many other services provided to the aviation community, including routine forecasts for air terminals and routes, and information that the Federal Aviation Administration transcribes for dissemination by 70 automatic telephone answering services and by continuous radio broadcasts from 104 transmitters.

There are a number of other services that indirectly benefit the public. Twelve River Forecast Centers not only provide flood warnings, but also regularly issue forecasts of river stages, volume of flow, water temperature, ice formation and breakup, and seasonal supply of water. These hydrological services are used by agencies that manage water, and a good example is for the Columbia River Basin, that drains half of the West. Water management there must take into account needs for flood control, hydroelectric power, irrigation, river ports, and salmon spawning.

Specialized services are also provided for marine navigation and fisheries, air pollution, agriculture, and forest fires. Over 200 people are devoted to these activities. Nineteen mobile units in the West are available to be deployed to the scene of major forest fires and to give direct support to fire fighters. Agricultural meteorologists in the field monitor specialized local observations for farming areas, make studies of how weather affects crops, provide advisories to extension services and farm businesses, and tailor forecasts for farming operations. They also work directly with farmers. Advisories on air stagnation potential, issued from 52 points to public and local control agencies, activate the first stage of control of air pollution incidents. Marine forecasts and warnings for the Great Lakes, North American coastal waters, and for the high seas over more than a quadrant of the globe are issued by designated stations, and are broadcast continuously by NOAA Weather Radio. They are also carried several times daily by Coast Guard, Navy, and commercial radio stations. Severe storms, ice, wave and swell, and other marine hazards are included.

Services to the public are decentralized, with about 250 Weather Service Offices scattered about the country. Weather Service Offices provide the most direct outlet for weather information to the general public. They are staffed mostly with skilled technicians. The basic information is produced and provided at two other levels in the hierarchy. Fifty-two Weather Service Forecast Offices each produces forecasts generally covering an area the size of a midwestern state, and each provides information to several Weather Service Offices. Weather Service Forecast Offices are staffed with highly trained professional meteorologists and hydrologists.

To avoid duplication of much work in the many Weather Service Forecast Offices, and to do it best and most economically, there are three national centers. Two of them are highly specialized to deal with special weather phenomena. The National Severe Storms Forecast Center in Kansas City, Missouri, issues forecasts of small destructive storms--severe thunderstorms, hailstorms, and tornadoes. The National Hurricane Center in Miami, Florida, issues watches and warnings of hurricanes threatening the country. More basic and routine daily guidance for the field forecaster is provided by the National Meteorological Center (NMC) near Washington, D. C. All of the offices and centers of the National Weather Service are linked with several teletype and facsimile networks, carrying both weather observations and forecasts. The NMC transmits the bulk of the forecast information on the networks, about 500 facsimile charts daily, and a half million teletype groups. Weather forecasts prepared at NMC are 85% automated, cover the globe, and are prepared by numerical weather prediction. The most powerful computers on the market are required, which is a sufficient reason for centralizing the function.

The scientific problem

The atmosphere is basically a mixture of gases and therefore is particularly free in its movements. Its motions are constituted of broad wind fields and vortices which themselves move and change constantly and are of all sizes and scales. At one end of the scale there is a jet stream 10 km high in the temperate zone of each hemisphere, circling the two poles as vast, ever-present vortices. Like giant snakes, the jet streams undulate slowly north and south in very long waves, up to five or so about the globe. Next down the scale are the large cyclonic storms and anti-cyclones, several hundred to several thousand kilometers across, which produce much of our snow and rainfall. Further down the scale are sea-breezes and thunderstorms, tens of km across; then circulations such as tornadoes and water spouts, up to a few hundred meters across. Then on down the scale are dust devils, wind gusts, and finally, phenomena not clearly distinguishable from the molecular scale. Strictly speaking, every flap of a gull's wing causes a circulation that interacts with all other scales of circulation, and forever changes their future course.

To complicate all this, one constituent, water, changes phase readily from vapor to liquid to solid, with accompanying large releases and absorptions of heat. Condensed water in the form of clouds dramatically changes the radiative properties of the atmosphere, as does snow and ice cover change that of the earth's surface. Water is continually cycling through the atmosphere, evaporating in one place--mainly over oceans and other bodies of water--and falling to earth as rain and snow in another. The atmosphere interacts with both the surface it passes over, and through radiation with outer space and the sun. There are mountains and plateaus it ascends and descends, and continents and oceans it crosses, each having its own characteristic variability of underlying drag, radiative, and evaporative properties.

The mathematics are also complicated. Shown in Figure 1 are the fundamental laws for a gas, stated in mathematical terms. As shown, they apply to a dry, frictionless, adiabatic atmosphere. Heating and friction are important, especially for atmospheric predictions beyond a week, but are not overriding for large-scale motions over periods of a few days. I show this set of six simultaneous equations, less some of the terms we use, to illustrate the difficulty of the weather prediction problem when posed as a problem in mathematical physics. Note that the set is nonlinear, a characteristic which has led to a great deal of applied mathematical work in the field. Fortunately the terms with derivatives in time are linear and first-order; weather prediction is an initial-value problem. The set is also partial in time and three-dimensional space, so we must deal with four-dimensional fields of data. The atmosphere is a mightily complex system to predict, but perhaps no more so than many other geophysical systems.

Such are the problems arrayed against us. What do we have going for us in our attack? We have observations, communications, and computer power, but most fundamental of all we are dealing with an orderly physical system.

Order in the atmosphere

A necessary condition for numerical weather prediction to work is that the atmosphere be orderly in great degree. At least, the scale of events being predicted must not be overwhelmed in a disorderly way by interactions with smaller scales that are not explicitly accounted for in the predictive system. Indeed, in practice these smaller scales are generally unobservable, and may even be unpredictable in principle for the periods being forecast. A first casual survey of the atmosphere would likely impress an untutored observer with the randomness of weather events and their apparent unpredictability, except for the clearly evident diurnal and annual cycles. Careful and direct observation, however, reveals order on all scales. A half decade of abnormally warm winter weather in the eastern United States was completed in 1976. When winter (December through February) temperature averages in the East for the 10 years beginning with December 1965 are broken down into yearly winter averages, we find not randomness, but a distinct pattern. Take for example winter temperatures at Atlanta, Georgia, as shown in the table.

Atlanta, Georgia

year	departure from 1965-75 mean (Dec-Feb)
1965-66	-2.3 °F
1966-67	-0.8
1967-68	-2.1
1968-69	-2.8
1969-70	-3.3
1970-71	+1.1
1971-72	+3.4
1972-73	+0.4
1973-74	+3.9
1974-75	+2.4

Each yearly winter anomaly is directly associated with shifts in the mean positions of meanders in the jet stream, but more to the point, the sequence more than suggests large-scale long-term mechanisms. Admittedly, this is not the best example of orderliness, its principal weakness being that such events remain unpredictable. On the other hand, such persistence should and does motivate many atmospheric scientists to search for causes and underlying order.

The predominance of vortices in the atmosphere is an important feature of the atmosphere from the standpoint of predictability. Vortices in a fluid that is not forced, or in which external forcing is small and/or slow-acting, are longer lived, are slower to move and develop, and are slower to exchange mass with their environment, and energy with other scales, relative to other types of fluid motions. Vortices, in other words, are characteristically orderly fluid systems.

The recent Bicentennial celebration reminds us that it was one of our nation's founders, Benjamin Franklin, who in 1743 was among the early discoverers of the circular nature of storms, events that are characteristically 1-5000 km across. The discovery that the storm scale is overwhelmingly dominated by vorticity* must have caused much optimism at the time about predicting the weather. Indeed in 1870, only 26 years after Morse relayed the world's first telegraphic message, "What hath God wrought," from Washington to Baltimore, Congress created a national weather service in the Signal Corps of the U. S. Army.

By 1870 the Corps had established a national telegraphic network, allowing quick communication of widespread observations to a central location. Development of synoptic meteorology, based on analyses of observations taken simultaneously over a large area, soon followed (Mitchell and Wexler, 1941). The result was a forecast methodology of mapping wind, temperature, humidity, cloud, and rainfall systems on sequential charts, noting their movements, accelerations, and developments, and predicting principally through persistence and trends. Soon added to these primary tools were such physical relations as could sketchily be drawn from natural laws, and a wealth of experience and art accumulated by individual forecasters. Such techniques can be successfully applied only to natural systems with a high degree of order.

Also, the first operational numerical weather predictions depended on the predominance of vorticity in the atmosphere on the storm scale. When the world's first electronic stored-program computer was being designed and built at the Institute for Advanced Study, Princeton, New Jersey, weather prediction was among a very few problems chosen for its first applications. By the time the machine was up and running, John von Neumann, Jule G. Charney, and a group of scientists at the Institute had devised an atmospheric prediction model (Charney, et al., 1950). They drew on the earlier ideas of C. G. Rossby (1939) that earth's rotation and the distribution of heating and cooling between the equator and poles give rise to the principal mechanism of the atmosphere's behavior, and within a year had proven feasibility

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*Vorticity is a measure of the extent to which a small body of fluid is rotating about an axis. For example, water rotating in a pail has vorticity about a vertical axis. Trailing wing tip vortices from an airplane in level flight have vorticity about a horizontal axis.

of numerical weather prediction (Charney and Phillips, 1953). The only physical mechanism contained in the first model was the rearrangement in the horizontal of the vertical component of vorticity. Charney treated the whole vertical structure of the atmosphere as one layer, depending on the high auto-correlation between the wind and temperature fields in the vertical. He also depended on the geostrophic wind relation, a simple observed relationship between wind vector fields and horizontal pressure gradients. Charney's barotropic model, after some needed improvements were added, was the first skillful model to become operational in 1958. It is the extra-tropical storm scale and larger that Charney's model successfully predicted, and it is on those same scales that today's models succeed.

There is also order in the smaller scales. Thunderstorms are well organized circulations driven by simple buoyancy forces, with a characteristic period of an hour or so, and around the ascending air column there is a doughnut shaped vortex ring. With today's radar observations considerable success has been achieved in predicting displacements of thunderstorms once formed. The methods are the old ones of persistence and trends. Today the twin problems of detailed observation of the thunderstorm scale and the computer power that would be required appear overwhelming; but one day surely, even if it be the distant future, individual thunderstorms will be predicted with methods not unlike today's methods of numerical weather prediction.

Engineering and logistics problems

A discussion of numerical weather prediction would be incomplete without mentioning hardware systems necessary for it to be part of a public service. If I were asked to name the five most significant developments in the history of weather forecasting, I would include numerical weather prediction; but more to the point, prominent in the list would be inventions. I have put together such a list, shown as Figure 2. Each entry in the list generally covers a whole sequence of scientific and technological developments, which tends to subdue the importance of many individual breakthroughs. I would argue along with research scientists, that scientific breakthroughs following inventions such as those shown are not automatic. That is too strong a word, but they do appear inevitable.

Actually, the basic and fundamental laws (Figure 1) that we use today were well known a century ago. From that standpoint much that we do today would be understandable to a nineteenth century physicist, although the first clear recorded statement of the possibility of such a fundamental approach was not made until the twentieth century (Bjerknes, 1904). Forecasters in that day, however, lacked several necessary tools. For instance, they did not have observational systems required for numerical weather prediction. Observations were taken at the ground only, and at first the only information available about the upper air was from visual observations of clouds. The development of adequate observational systems was painfully slow. Beginning in 1894, observations were taken with box kites equipped with meteorographs to record pressure, temperature, and humidity. Kites were limited to heights of about 1 1/2 km, however, and they could not be released in unfavorable wind and weather conditions. They were also expensive and untimely. With cumbersome equipment, it took several men to fly a kite, and it took several hours for a kite to complete its ascent and return, and for the data to be reduced. There were never more than six stations in the United States equipped to take kite observations. It was in 1909 that upper winds were first observed by means of uninstrumented balloons and telescopes equipped to measure horizontal and vertical angles. Pilot balloon observations are limited in height to 6 km and clouds interfere with them, but they are quick, accurate, and inexpensive. Ninety-six stations in the United States are still equipped to take pilot balloon observations, although now only on call in special weather situations. Instrumented airplanes began taking upper air observations about the time of World War I, and by 1937 were flying daily from about 30 airports in the United States. Airplanes had many advantages over other means, but they were limited to heights of about 4 km, were very expensive, and could not fly in all weather.

All-weather three-dimensional observations did not come into being on an operational schedule until about the time of World War II. By that time the radiosonde had been developed, which consisted of pressure, temperature, and humidity sensors, together with a small radio transmitter in a light weight package tied to a balloon. The radio signals are intercepted and reduced at the ground. Radio direction-finders were later added to the system which give all-weather observations of wind. The rawinsonde gives observations to about 30 km. Thus it was not until the 1940's that a barely adequate observational system was established, limited to populated areas of the earth. Since then observational systems have been supplemented by wind and temperature observations at flight level from commercial aircraft, and by a wide variety of observations from satellites, including indirect soundings of temperature, cloud imagery, winds found by tracking clouds, sea surface temperatures, and snow and ice cover.

A telecommunications system is also required. Today's system is world-wide, and serves all nations. Set up by international agreement and participation, it is called the Global Telecommunications System (GTS). A principal feature of GTS is a trunk circuit girdling the globe, connecting Washington, Tokyo, Melbourne, New Delhi, Cairo, Moscow, Prague, Offenbach (near Frankfurt), Paris, and Bracknell (near London). From each of these hubs there are many feeder lines.

Several billion arithmetic and logical operations must be performed to complete one numerical prediction with today's models, and operational deadlines must be met. In this situation the fastest computers on the market are required, within constraints of hardware reliability and adequate systems software support by the vendor. Indeed, since the inception of operational numerical weather prediction in 1955, progress has been paced by advances in computer technology and continues to be. Figure 3, a plot of computer speed relative to the CDC 6600 against year of acquisition for operational use in the United States, shows that our present computer's speed is more than 500 times that of our first one. The straight line drawn through the IBM 701 and CDC 6600 shows that in the early years we were on an exponential growth curve of 53% compounded annually. The point labelled A has a speed typical of a few recently announced computers, and I have plotted it against the year 1980 as a reasonable time of acquisition. Computer A is farther off the exponential curve than our present computer, the IBM 360/195, which indicates that the growth rate is decreasing. Nowhere does nature support exponential growth indefinitely. Computer speed is increasing, however, and will continue to pace advances in operational numerical weather prediction.

In Figure 4 I've tried to indicate schematically the system built around the numerical weather predictions made in the National Meteorological Center. The numbers associated with the global observational subsystems are numbers of observations received daily at the central, and those below the National Weather Service offices are numbers of offices scattered around the country. At the heart of the operations in the National Meteorological Center are two computer complexes, a system of three IBM 360/40's and one IBM 360/30, and a system of three IBM 360/195's. The latter are top-of-the-line on the commercial computer market, and are rated at about 10-15 million instructions per second. There are two nearly identical basic cycles per day, and Figure 5 is for part of one of them, indicating the functions performed by each system.

Modeling and model performance

Numerical weather prediction is a direct approach to weather forecasting, in which the physical laws (Figure 1) governing the atmosphere are integrated from an initial state. The equations are for a continuous medium, while our computers are digital. The equations therefore are usually first transormed into partial finite-difference equations, in which derivatives are replaced by difference ratios. This step in itself has generated what might be called a scientific discipline in its own right (e. g., Phillips, 1959; Arakawa, 1966; Marchuk, 1967; Shuman, 1974). An alternative to finite-differences in space is a transformation from real physical space dimensions to amplitudes of orthogonal functions in one, two, or three space dimensions. The most recent development combines the two approaches (Bourke, 1974) and has already become operational in Australia and Canada.

I will use currently operational models of the National Meteorological Center (NMC) to illustrate the construction of a model. A finite-difference net is first constructed in three dimensions. Figure 6 shows the vertical structure of a net that is used for several NMC models, including the Hemispheric Model (Shuman and Hovermale, 1968). Figure 7 indicates schematically the area and horizontal nets for several NMC models, including the Hemispheric Model, the Regional Model, the experimental Very Fine-mesh Model (VFM), and the Hurricane Model (HCN). The area shown for the latter is small but relocateable, and can be placed to cover a feature of particular interest. The area of integration can also be moved during the prediction so that it remains centered on the feature of interest. In practice the area is kept moving in this way when it is used to predict hurricane displacements.

In each model, the dependent variables listed in Figure 1 are first "analyzed." Simply put, an analysis consists of interpolation from the irregular array of observations to the regular array of the model net. This, however, is an oversimplification indeed. A numerical analysis must take into account the scale of features being analyzed, inevitable errors in the data, large variations in the density of the data, hydrostatic balance, and certain delicate balances in the atmosphere between the wind and pressure fields. Several alternative methods have been developed, including local fits to conic sections (Gilchrist and Cressman, 1954), use of influence functions (Bergthorsen and Doos, 1955; Cressman, 1959), statistical weighting (Gandin, 1963), and use of orthogonal functions (Flattery, 1970). Lately we have had to deal with data that is asynoptic, i.e., not synchronous, but spread unevenly around the clock. The principal source of such data is satellites and commercial aircraft. Analysis has thus become a four-dimensional problem, in time as well as space. To distinguish the older problem from the newer, it has come to be known as four-dimensional data assimilation.

The three-dimensional distribution of dependent variables being thus given at a moment of time, the space derivatives are calculated using difference approximations, and the rate of change in time is then calculated using the equations. Assuming the rate of change is constant during a small interval of time (e.g., 10 min), new three-dimensional fields of the variables are calculated, and the process is repeated until the desired forecast period is reach.

How well has numerical weather prediction performed? Figure 8 shows a history of skill at NMC of the 36-hr circulation prediction at 500 mb, the atmospheric half-mass level. It can be seen that during the 20-year era of numerical weather prediction, the skill by this measure doubled from about 30% to about 60%. Predicted circulation patterns at other levels in the atmosphere experienced a similar increase in skill, and the viability of circulation forecasts also roughly doubled, from about three days to about six.

Numerical weather prediction has also had a beneficial effect on forecasts of precipitation, although the record is not as bright. Consistent long-term verifications of precipitation forecasts are few; complete records exist for only the past decade. Forecasts of whether or not rain will occur have been kept since 1954, however, for Boston, Chicago, and Washington. Figure 9 shows the percent correct, year by year averaged for those stations, and also for more than 50 stations since 1966. Note that there was a gradual improvement at the three stations until the middle 1960's, after which both curves were fairly level until 1976. This is consistent with the record for circulation forecasts shown in Figure 8, and is attributed to the impact of numerical weather prediction.

The high score for 1976 carries an implication that this kind of weather forecast may be ascending to a new plateau of skill. Late in May 1976 the National Meteorological Center began issuing a new guidance product to the field, namely, an extension of predictions made with the Regional Model to 48 hr, to cover the periods of the forecasts whose scores are shown. The weather of 1976 was itself unusual over the United States, and the unusually high score might be a reflection of that. However, the new guidance product has not been fully exploited yet, and some improvement should be expected when it is.

More important to the general public are forecasts of amounts of precipitation. By 1960 it was realized at NMC that numerical weather prediction had become a powerful new tool for quantitative precipitation forecasting. In September 1960 a specialized group of meteorologists was created in NMC to take full advantage of the new tool. Figure 10 shows that the skill of NMC guidance immediately and sharply reacted. Note that there is little indication of subsequent improvement. I don't believe, however, that a limit of predictability of quantitative precipitation forecasting has been reached. We have important new evidence on this point that I will discuss later.

Quantitative precipitation is one of the most difficult forecasts to make. It is the end result of a long chain of atmospheric processes, and errors in each link of the chain tend to multiply in quantitative precipitation forecasting. In infrequent cases of very large scale precipitation, say covering most of the mid-West, forecast amounts are remarkably good. Usually, however, precipitation falls on smaller scales, and accumulations tend to be arranged along axes with cross-axis dimensions of 100 km or so, while an axis may be as long as 1000 km. There is even much finer-grain detail within precipitation areas, down to one km or less, and with periods of a few minutes. Summer showers are good examples, but even what we ordinarily regard as large scale precipitation has such fine-grained detail. As noted earlier, through use of weather radar, some success has been achieved in forecasting such detail for periods of an hour or so, but success on very fine scales for much longer periods isn't in sight. Highly detailed predictions of precipitation amount are not required for them to be highly useful, however. Consider the problem of flash floods, for example. A watershed into a river or stream "integrates" rainfall into accumulated runoff and flood water, and the detail of the rainfall pattern over the catchment matters little.

Plans and predictability

The problem of quantitative precipitation now appears ripe for attack. We have mounting evidence that increasing the horizontal resolution of our models will improve not only wind and temperature forecasts, but also precipitation forecasts. Figures 11 and 12 show graphically the effects of varying resolution for a selected case. We have similar results for several other cases, and the sequence shown is typical of what should be expected regarding resolution versus skill. The case is of an incipient frontal wave initially over the Gulf of Mexico, that developed in 48 hr and moved to the conjunction of Indiana, Ohio, and Kentucky. Note in Figure 11 that the Hemispheric Model did not capture the important events at all, but progressive skill is shown by the other models as the grid size is reduced, expecially in the location of the low center. It should be noted that the difficulty of the Hurricane Model (60 km) over the Gulf tier of states is probably due to boundary problems. Its southern boundary is just about at the border of the display. In this run, its boundary values were taken from the Hemispheric Model, and so it could not properly close off the low to the south. Note that it did, however, exactly place the low center.

Of significance to forecasting the weather itself, Figure 12 shows the corresponding predictions of 12 hr accumulations of precipitation. Again, progressive skill is shown as resolution is increased. The NMC has gathered other evidence of the benefits of higher resolution to the forecast, some of which is published or being published (Brown, 1976; Newell, 1977; Fawcett, 1977).

The Regional Model has the highest resolution (168 km) of the models that are run regularly twice daily. In June 1976, however, the Hurricane Model was implemented, but is not run regularly. It was originally developed to track hurricanes and is on call to be run with a 60 km grid when a hurricane treatens the United States. In conference with field hydrologists, it is also run with a 100 km grid when there is a threat of major flash floods. As of May 1977, it has been called about 40 times.

Higher model resolution over larger areas requires more computations, but fortunately we have not fully exploited the IBM 360/195 system yet, and we believe that some improvements can still be made with this resource.

For two years or so the National Meteorological Center has had available about half of the resource consisting of three IBM 360/195's, operated by a parent organization, the National Oceanic and Atmospheric Administration (NOAA). The IBM 360/195's, rated at 10-15 million instructions per second (MIPS), replaced a system of three CDC-6600's, rated at 2 MIPS. The high speed of the new machinery, relative to the old, is required for advances in modelling, particularly for models with higher resolution. To date, the area covered by the Hemispheric Model has been enlarged by 40%, and the forecast period of the Regional Model has been doubled from 24 hr to 48 hr, but otherwise the full power of the new machinery has not been used in NMC operations. A number of experiments with more highly resolved models have been carried out, however, and NMC has recently made definite plans for replacing both the Hemispheric and Regional Models in 1977 (Shuman, 1977).

In the case of the Regional Model, the plan is to replace it with essentially the same model covering the same area, but with its grid interval reduced by 30% to 50%. This will double its running time to one hr per 48 hr forecast, a limit imposed by operational deadlines. Replacement of the Hemispheric Model will be more complicated because three candidates have been developed. One is simply the presently operational model with its grid interval halved. The other two have more vertical resolution, up to 10 levels, more sophisticated physics, and different numerical systems. The plan is to run them in competition with each other on several selected cases, select one, and test it extensively against the operational model to determine that it indeed does have more skill.

What of the more distant future? The limits of the present computers will have been reached by 1978. The more highly resolved models should respond more clearly to physical effects, however, and major research efforts will therefore be devoted to improvement of model physics. Such improvements are expected to little affect running time of the models. Meanwhile, in 1977 NMC is embarking on a project to address the question of optimum resolution. This effort is related to the question of a new computer acquisition in the early 1980's. The problem simply stated is to determine whether or not an increase of model resolution beyond the operational capabilities of the present machinery will yield increases in forecast accuracy sufficient to justify the cost of a new more powerful machine. The limited amount of available evidence, such as that shown earlier here, indicates an affirmative answer. This is particularly so of improvements in forecasts of amount of precipitation, whose larger scales are barely even definable with the resolution of the coarser-meshed operational models.

There are limits, however, to the predictability of the atmosphere. Because we are not, and never will be, able to observe the atmosphere everywhere down to its finest-grain detail; and because this detail, these small scales, affect the larger scales; a limit imposed by observational systems must exist on predictions of the larger scales. A few sketchy theories have appeared on this subject (Lorenz, 1969; Robinson, 1971) that go further, and indicate that there is a fundamental uncertainty, independent of how thoroughly the atmsphere is observed. Generally, the theories relate the period of predictability to the scale being predicted; the smaller the scale, the shorter the period. Such a notion should be quite plausible to a seasoned forecaster. Implied in these theories, of course, is that achievable skill gradually decays to zero during the period of predictability, which universally fits with experience.

How do the theories relate to ongoing efforts in numerical weather prediction? From experiment, we believe that we can increase the skill and extend the period of operational predictions. We do not know, however, to what extent this can be done in principle. The infant theories of predictability indicate that the storm scale is predictable up to a few, a very few, weeks. Presently we are limited to less than a week. The theories, sketchy as they are, thus support our search for optimum resolution of models. At any rate, the theories have not been tested, and must be. To paraphrase Georges Clemenceau (1841-1929), Les prévisions du temps! c'est une chose trop grave pour la confier à des théoriciens.

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References

Arakawa, A., 1966: Computational design for long-term numerical integration of the equations of fluid motion: Two-dimensional flow. Part I. Journ. Computational Physics, 1, 119-143.

Bergthorssen, P., and B. Doos, 1955: Numerical weather map analysis. Tellus, 7, 329-340.

Bjerknes, V., 1904: Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik. Meteor. Z., 21, 1-7.

Bourke, W., 1974: A multi-level spectral model. I. Formulation and hemispheric integrations. Mon. Wea. Rev., 102, 687-701.

Brown, J. A., 1976: Modelling and the man-machine mix at the National Meteorological Center. Papers Presented at the WMO Symposium on the Interpretation of Broad-scale NWP Products for Local Forecasting Purposes, Warsaw, 11-16 October 1976. World Meteorological Organization, Geneva, WMO-No. 450, 151-158.

Charney, J. G., 1954: Numerical prediction of cyclogenesis. Proc. Nat. Acad. Sci., U.S., 40, 99-110.

Charney, J. G., R. Fjortoft, and J. von Neumann, 1950: Numerical integration of the barotropic vorticity equation. Tellus, 2, 237-254.

Charney, J. G., and N. Phillips, 1953: Numerical integration of the quasi-geostrophic equations for barotropic and simple baroclinic flows. J. Meteor. 10, 71-99.

Cressman, G. P., 1959: An operational objective analysis system. Mon. Wea. Rev., 87, 367-374.

Cressman, G. P., 1963: A three-level model suitable for daily numerical forecasting. Technical Memorandum 22, National Meteorological Center, National Weather Service, NOAA, U.S. Department of Commerce, 25 pp. + 15 figs.

Fawcett, E. B., 1977: Current capabilities in prediction at the National Weather Service's National Meteorological Center. Bull. Amer. Meteor. Soc., 58, 143-149.

Flattery, T. W., 1970: Spectral models for global analysis and forecasting. Proc. of Sixth AWS Tech. Exchange Conference, U. S. Naval Academy, Sept. 21-24, 1970, AWS Tech. Rep. 242, 42-54.

Gandin, L. S., 1963: Objective Analysis of Meteorological Fields English translation by Israel Program for Scientific Translations, Jerusalem, 1965, 242 pp.

Gilchrist, B., and G. P. Cressman, 1954: An experiment in objective analysis. Tellus, 6, 309-318.

Lorenz, E. N., 1969: The predictability of a flow which possesses many scales of motion. Tellus, 21, 289-307.

Marchuk, G. I., 1967: Numerical Methods in Weather Prediction. English translation by K. N. Trirogoff and V. R. Lamb, edited by A. Arakawa and Y. Mintz, Academic Press, New York and London, 1974, 277 pp.

Mitchell, C. L., and H. Wexler, 1941: How the daily forecast is made. Climate and Man, 1941 Yearbook of Agriculture, U.S. Dept. of Agriculture, U.S. Govt. Printing Office, Washington, D. C. pp. 579-598.

Newell, J. E., 1977: The NMC LFM model: status, performance, and prospects. Submitted for publication in Mon. Wea. Rev.

Phillips, N. A., 1959: An example of non-linear computational instability. The Atmosphere and the Sea in Motion, Rockefeller Institute Press, New York, 501-504.

Robinson, G. D., 1971: The predictability of a dissipative flow. Quart. J. Roy. Meteor. Soc., 97, 300-312.

Rossby, C. G., and collaborators, 1939: Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action. J. Marine Res., 2, 38-55.

Shuman, F. G., 1974: Analysis and experiment in nonlinear computational stability. Proceedings of the Symposium on Difference and Spectral Methods for Atmosphere and Ocean Dynamics Problems, 17-22 September, Novosibirsk, 1973. Part I, 51-81.

Shuman, F. G., 1977: Plans of the National Meteorological Center for numerical weather prediction. Office Note 144, National Meteorological Center, National Weather Service, NOAA, U.S. Department of Commerce, 14 pp. + 5 figs. Unpublished manuscript.

Shuman, F. G., and J. B. Hovermale, 1968: An operational six-layer primitive equation model. J. App. Meteor., 7, 525-547.

Teweles, S., and H. Wobus, 1954: Verification of prognostic charts. Bull. Amer. Meteor. Soc., 35, 455-463.

Legends

Figure 1. The basic equations for a perfect gas.

Figure 2. The five most significant developments in the history of weather forecasting.

Figure 3. Operational computer speed, relative to the CDC 6600, against year of acquisition for NMC use.

Figure 4. A schematic of the U.S. forecasting service.

Figure 5. A schematic of the data flow, for the Hemispheric Model, through the NOAA computer systems.

Figure 6. Vertical structure of the Hemispheric Model, the Regional Model and the Very Fine-mesh Model. The dependent variables are carried for the layers between the curves, which are coordinate surfaces. The equations shown in Figure 1 are first transformed from the Cartesian coordinates, x, y, z, to a set of coordinates in which earth's surface is a coordinate surface. The artificial layer at the top is finite in height, and replaces the atmosphere there in order to avoid its unboundedness.

Figure 7. Horizontal area and a sample of the grids for several models. The grid sample for each model is shown in a corner of each area.

Figure 8. Record of skill, averaged annually, of the NMC 36 hr 500 mb (about 5.6 km high) circulation predictions over North America. The horizontal bars show average for the years during which no major changes in models occurred. Years of transition are not included in the averages. The "geostrophic" model (Cressman, 1963) is a generalization of the barotropic model, to account for baroclinic effects. The last bar shows the effect on skill of a change in input wind. Prior to 1972 a quasi-geostrophic wind field, derived from the pressure field, was used for initial winds. During 1972 analyses of observed winds were used instead. The measure of skill is based on the so-called S_1 score (Teweles and Wobus, 1954), that is in turn a measure of normalized error in horizontal pressure gradients. A chart with an S_1 score of 20 is virtually perfect, and one with 70 is worthless. As shown, skill (percent) is $2 \times (70 - S_1)$, which yields zero for a worthless chart, and 100 for a virtually perfect one.

Figure 9. Record of skill of public forecasts of whether or not precipitation will occur in a 12 hr period. The measure of skill is percent correct. The longer record is the average for the three stations listed, also averaged annually and for three periods after issuance, 0-12 hr, 12-24 hr, and 24-36 hr, except for Chicago, for which records of the first period were not available. The shorter record, 1966-76, is for all Weather Service Forecast Offices, but the first period, 0-12 hr, after issuance is not included. The higher scores for the three stations are largely due to inclusion of the first period.

Figure 10. Record of skill of the NMC guidance for more than 25 mm of accumulated precipitation during the first 24 hr after issuance. The measure of skill is threat score, which is the area of such precipitation correctly predicted, divided by the total area of such precipitation either observed or predicted. In the total, the overlapping area, i.e., the area correctly predicted, is not counted twice.

Figure 11. Forty-eight hour predictions of pressure at mean sea-level made with models of varying horizontal resolutions, from 335 km to 60 km. Only the last two digits of pressure in mb are shown in some of the charts. Thus, "12" means 1012 mb, and "88" means 988 mb. The predictions were started from observations made at 1200 GMT (0700 EST), December 24, 1975.

Figure 12. Predictions of accumulation of precipitation in mm during the last 12 hr period of a 48 hr forecast. The panels correspond one-for-one with those of Figure 11.

Newton's second law of motion

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu + \frac{1}{\rho}\frac{\partial p}{\partial y} = 0$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} + g + \frac{1}{\rho}\frac{\partial p}{\partial z} = 0$$

First law of thermodynamics

$$c_v \frac{dT}{dt} = p\,\frac{d\rho^{-1}}{dt}$$

$$\left(\frac{d}{dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right)$$

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

Equation of state for perfect gases

$$p = R\rho T$$

Unknown (time-dependent)

- u, v, w: x, y, z - components of velocity vector
- ρ: density
- p: pressure
- T: temperature

Known (time-independent)

- f : Coriolis parameter
- g : gravity
- c_v : specific heat at constant volume
- R : gas constant for air

Figure 1.

HIGHLIGHTS OF THE HISTORY OF WEATHER FORECASTING

-o- DISCOVERY OF CIRCULAR NATURE OF STORMS. (18TH CENTURY)

-o- INVENTION OF THE TELEGRAPH AND THE DEVELOPMENT OF SYNOPTIC METEOROLOGY. (19TH CENTURY)

-o- INVENTION OF THE RADIO, DEVELOPMENT OF THE RADIOSONDE, AND EXTENSION OF SYNOPTIC METEOROLOGY TO THREE DIMENSIONS. (EARLY 20TH CENTURY)

-o- INVENTION OF THE ELECTRONIC STORED-PROGRAM COMPUTER, AND DEVELOPMENT OF NUMERICAL WEATHER PREDICTION. (CIRCA 1950)

-o- DEVELOPMENT OF THE WEATHER SATELLITE AND EXTENSION OF THE OBSERVATIONAL SYSTEM TO COVER THE GLOBE. (CIRCA 1960).

Figure 2.

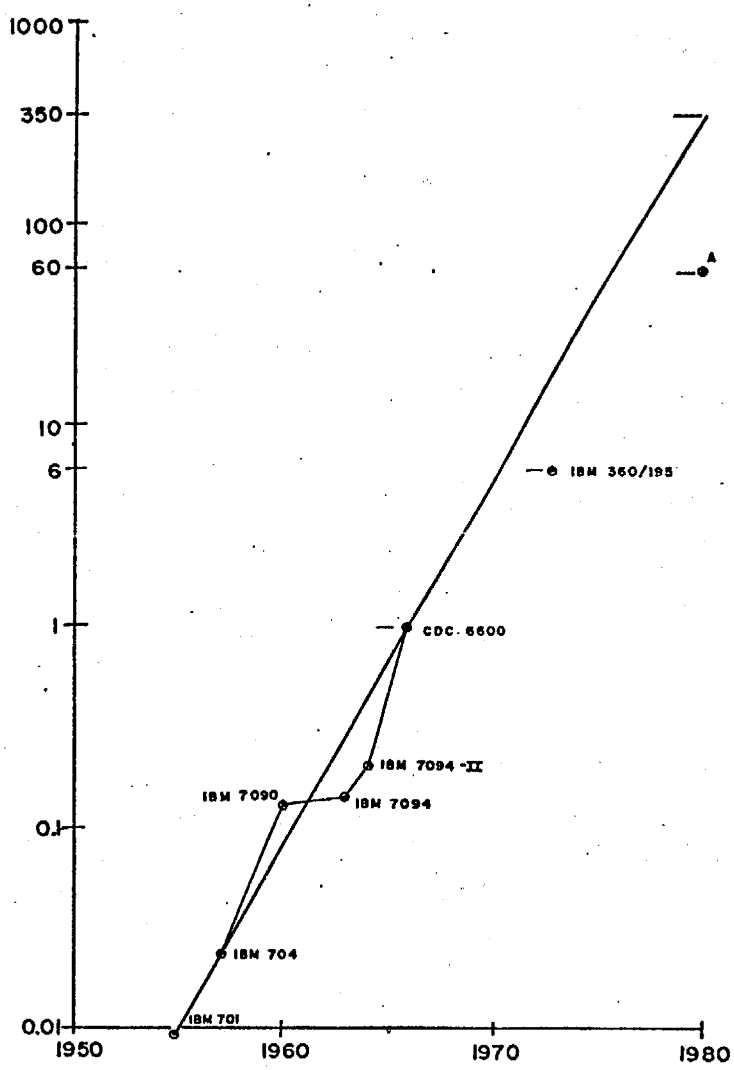


Figure 3.

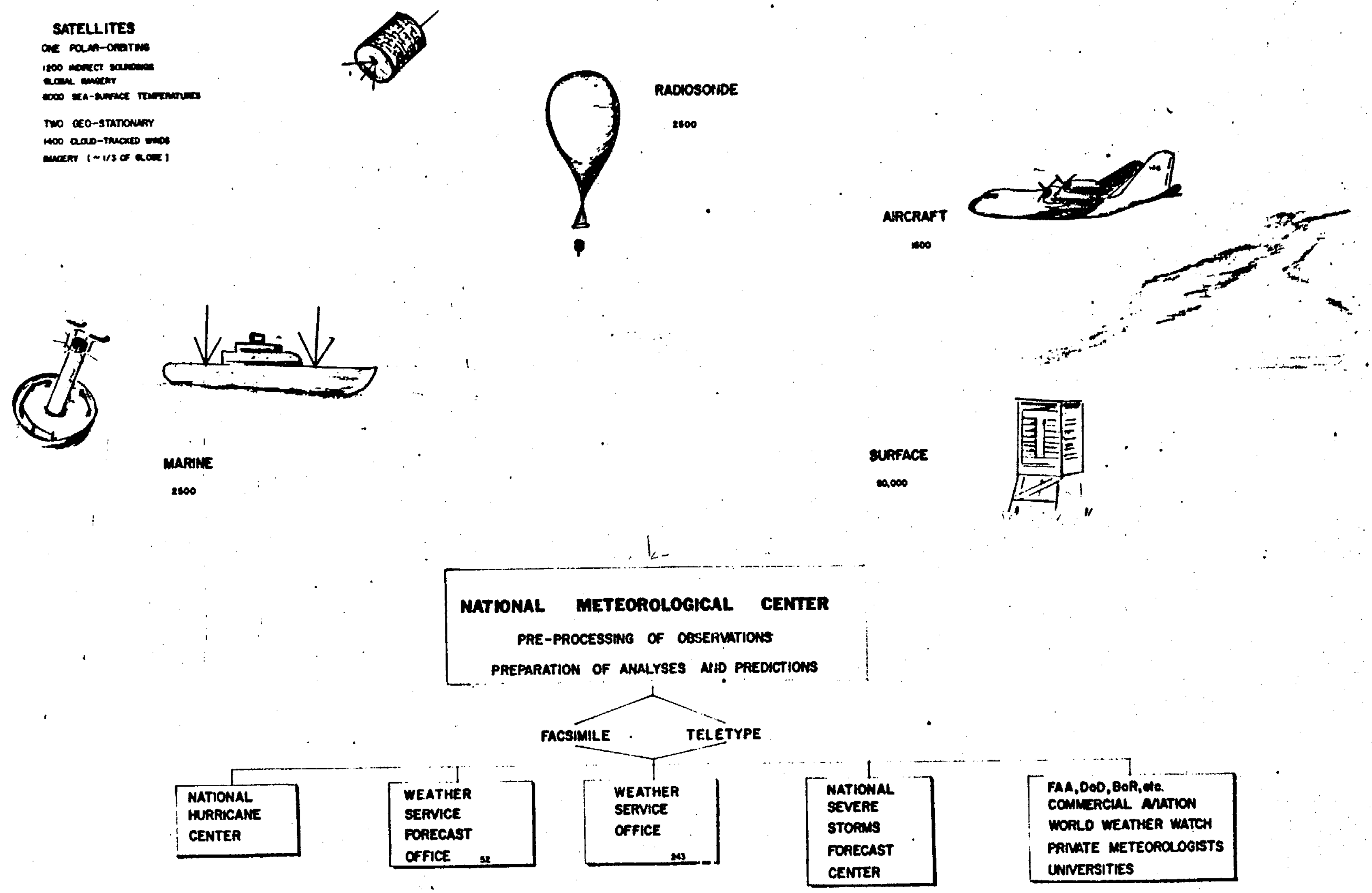
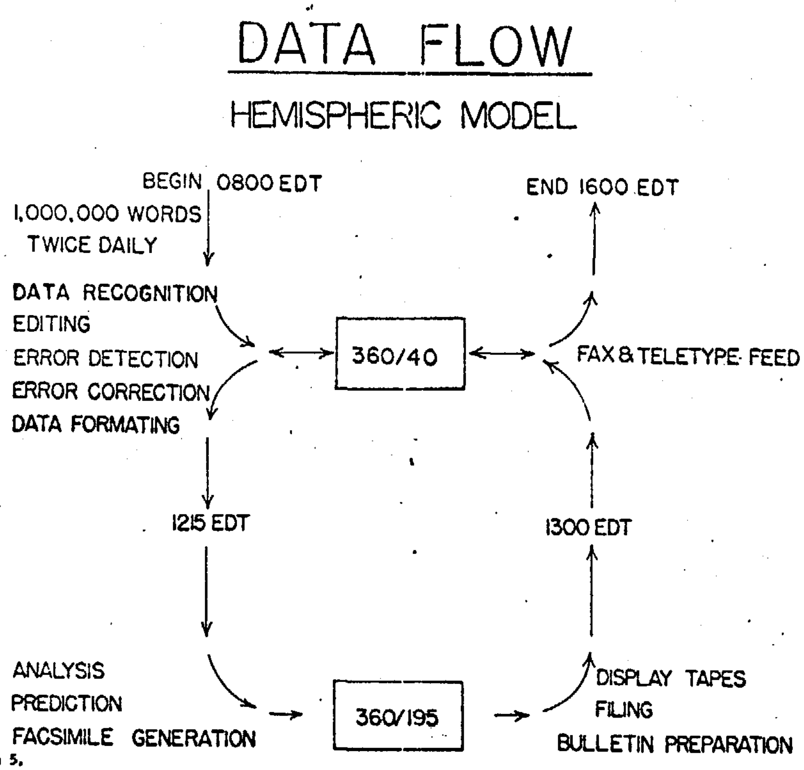

SATELLITES
ONE POLAR-ORBITING
1200 INDIRECT SOUNDINGS
GLOBAL IMAGERY
8000 SEA-SURFACE TEMPERATURES
TWO GEO-STATIONARY
1400 CLOUD-TRACKED WINDS
IMAGERY (~1/3 OF GLOBE)
RADIOSONDE
2500
AIRCRAFT
MARINE
2500
SURFACE
NATIONAL METEOROLOGICAL CENTER
PRE-PROCESSING OF OBSERVATIONS
PREPARATION OF ANALYSES AND PREDICTIONS
FACSIMILE
TELETYPE
NATIONAL HURRICANE CENTER
WEATHER SERVICE FORECAST OFFICE
52
WEATHER SERVICE OFFICE
243
NATIONAL SEVERE STORMS FORECAST CENTER
FAA, DoD, BoR, etc.
COMMERCIAL AVIATION
WORLD WEATHER WATCH
PRIVATE METEOROLOGISTS
UNIVERSITIES

Figure 4.



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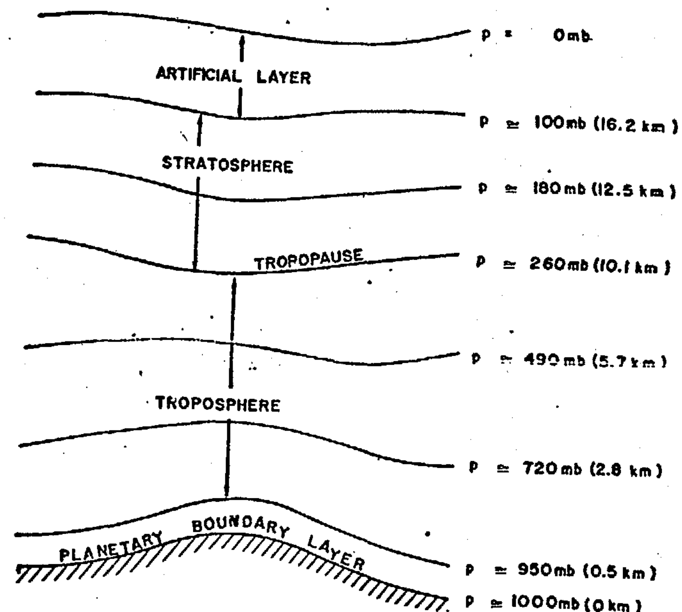

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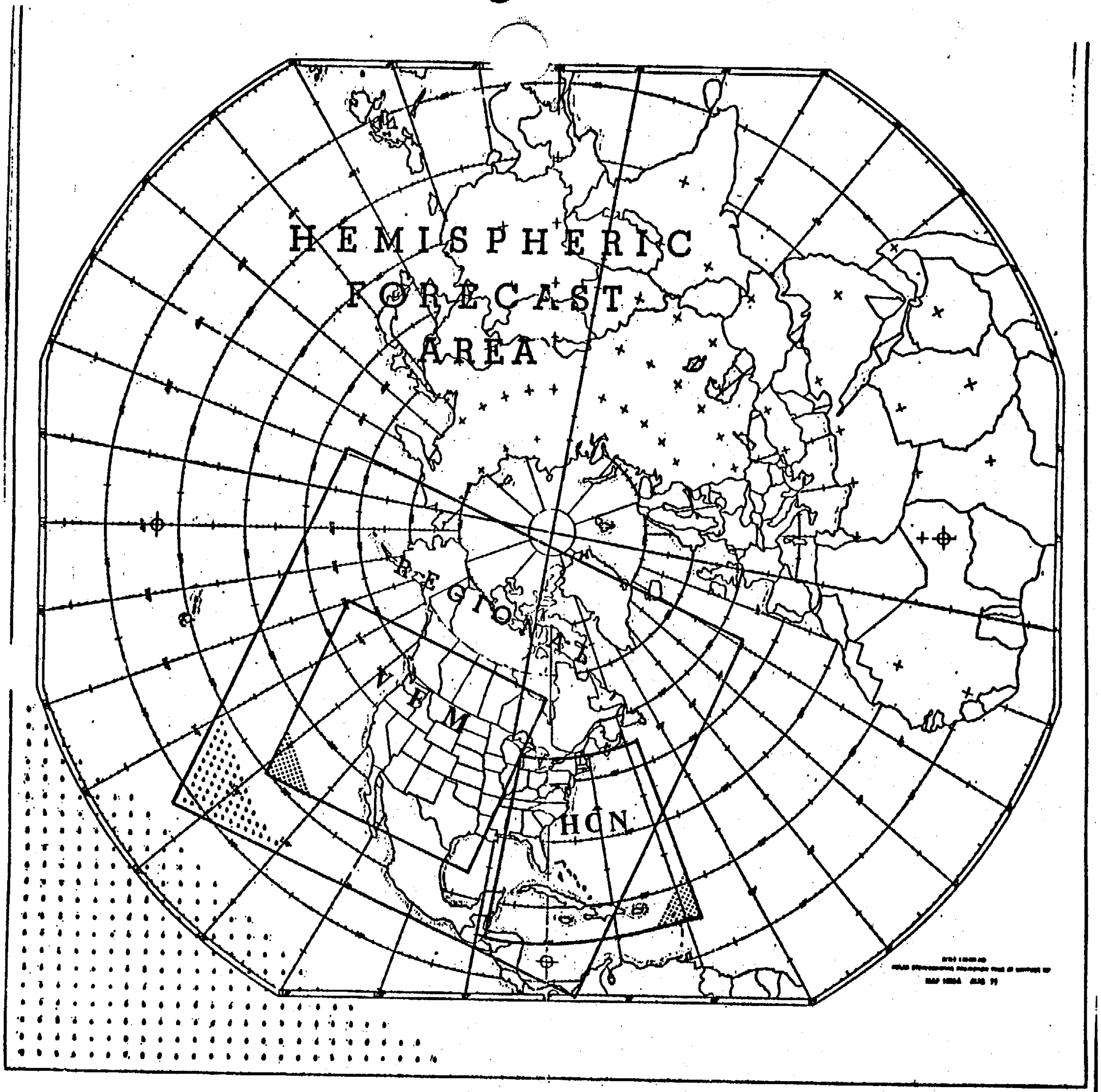

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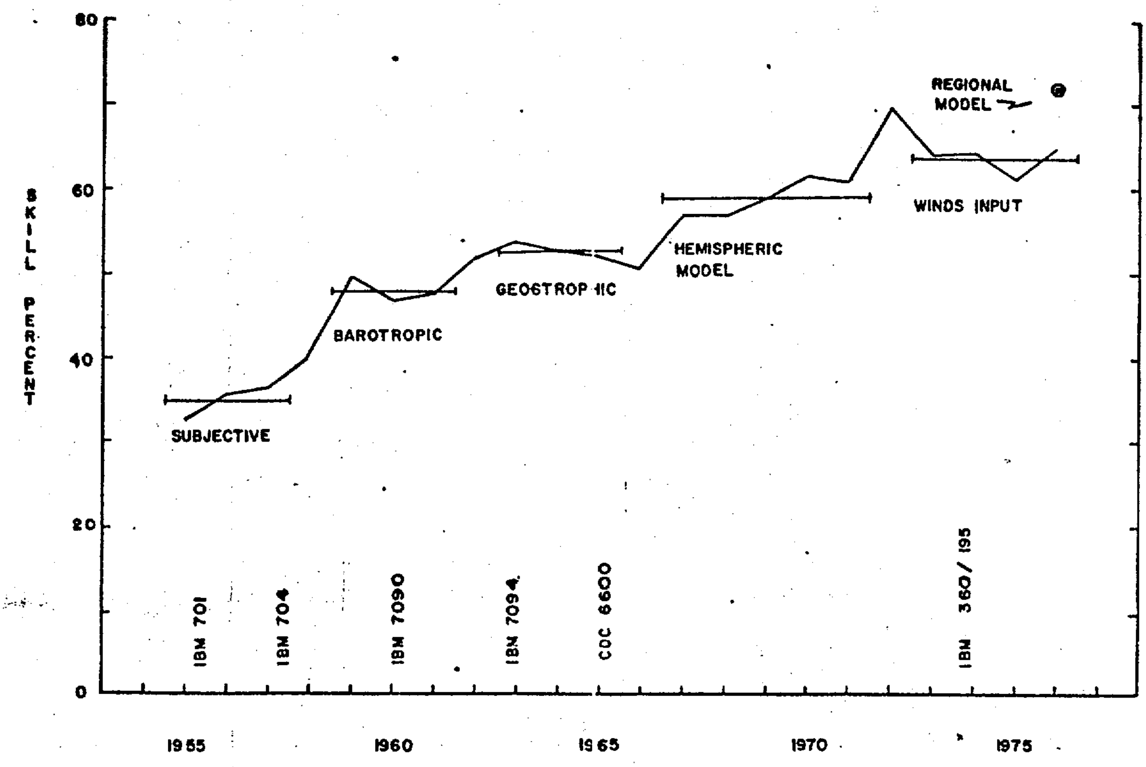

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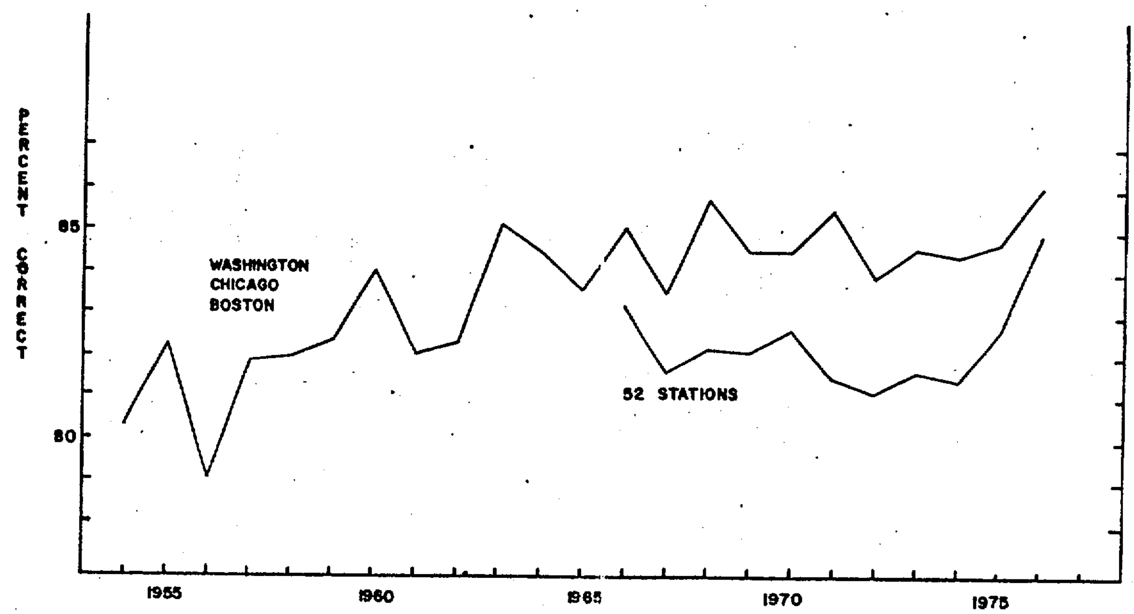


Figure 9.

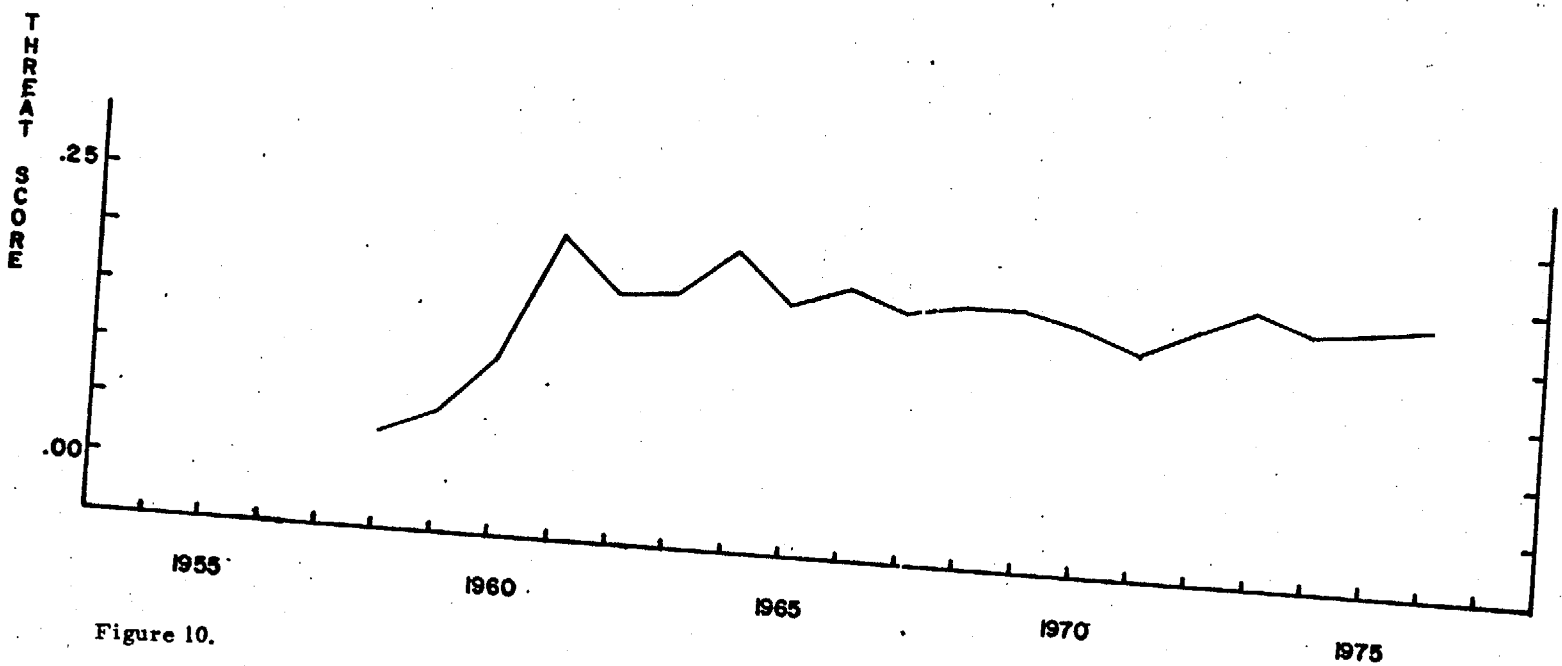


Figure 10.

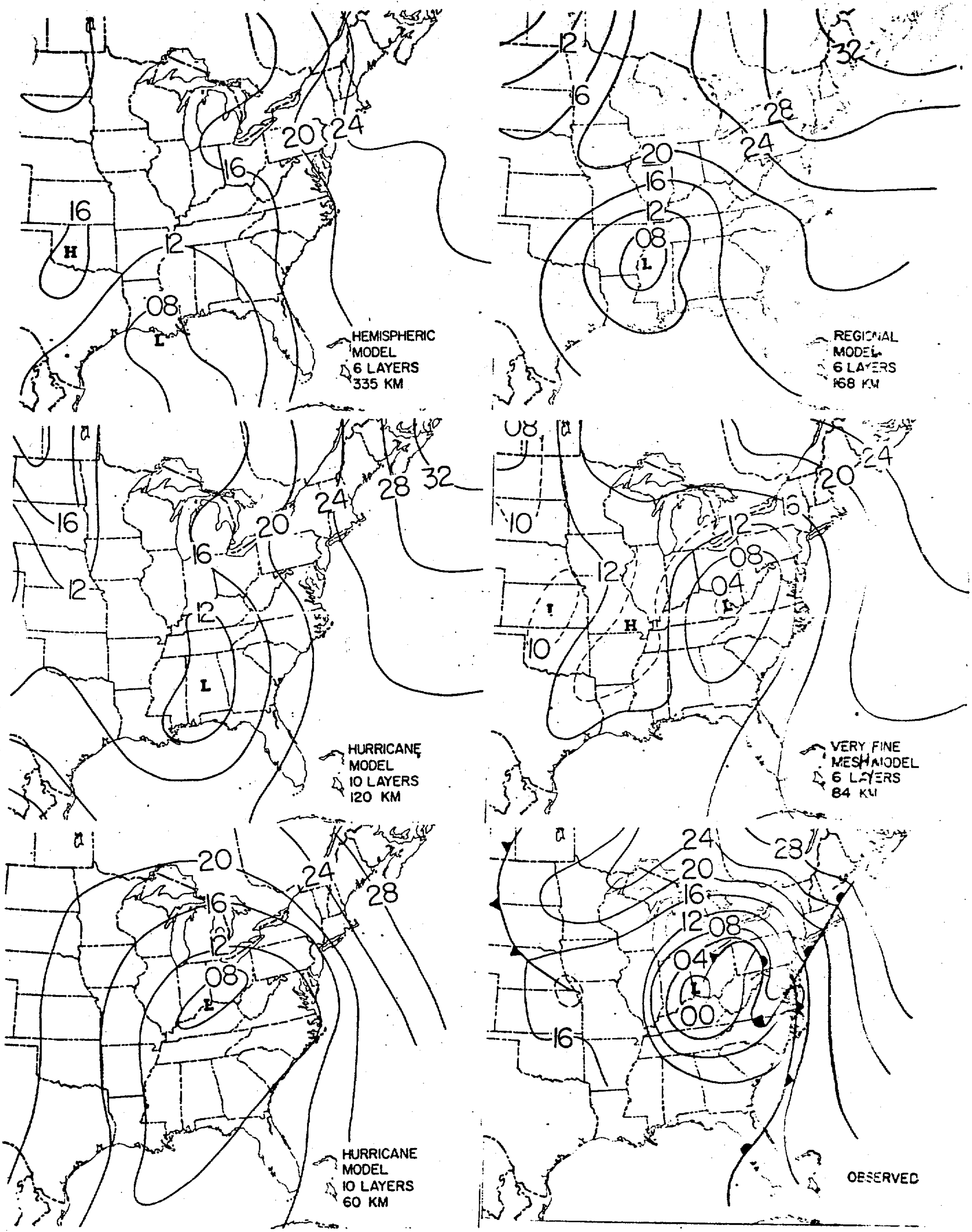
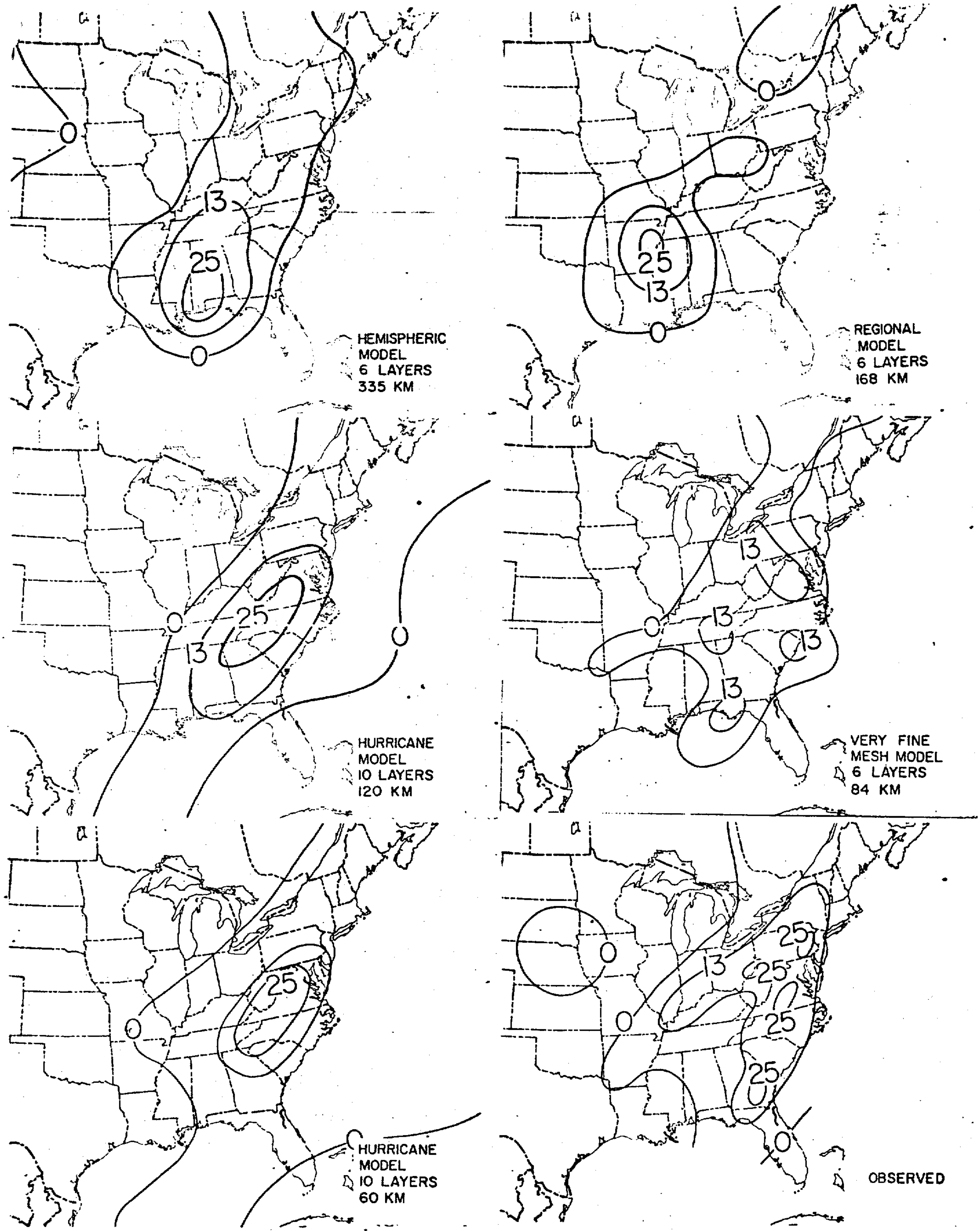

HEMISPHERIC MODEL
6 LAYERS
335 KM
REGIONAL MODEL
6 LAYERS
168 KM
HURRICANE MODEL
10 LAYERS
120 KM
VERY FINE MESH MODEL
6 LAYERS
84 KM
HURRICANE MODEL
10 LAYERS
60 KM
OBSERVED

Figure 11.



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HEMISPHERIC MODEL 6 LAYERS 335 KM
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VERY FINE MESH MODEL 6 LAYERS 84 KM
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HURRICANE MODEL 10 LAYERS 60 KM
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OBSERVED

Figure 12.